ALICE rf project meeting

Kai Hock, Cockcroft / Liverpool
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Status

- Aug - Dec 07: 4GLS beam loading (Hywel, Yuri)
  - Worked through Wiedemann's chapter, Perry Wilson's report on rf system
  - Reproduced simulation on 4GLS beam loading (Sakanaka ERL07)
  - Report on beam loading – basics, 4GLS

- Feb 08: ALICE rf control – new phase
- Mar 08: ALICE – intro to rf system (Andy)
- Apr 08:
  - Contacted, received paper, suggestions from Tom Powers
  - Looking up references: rf feedback, energy recovery theory, …
  - Started learning rf control hardware, set up by Andy
  - Idea: connect cavity / stretched wire to simulate beam loading
- May 08
  - Simulation on klystron power – with energy recovery ?
  - Set up stretched wire experiments ?

RF system theory

- Feedback control → experiments
  - Stefan Simrock's LLRF lectures
  - Papers on ELBE rf system

- Beam loading
  - Wiedemann's textbook, Wilson's SLAC report (beam loading)
  - Sakanaka's ERL07 paper (4GLS simulation)

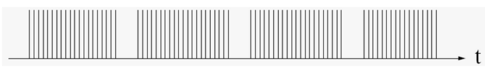
- Energy recovery linac
  - Thomas Schilcher's PhD thesis (microphonics, Lorentz detuning)
  - Lia Merminga's 2001 USPAS lectures (beam loading in ERL)
  - Tom Power's paper

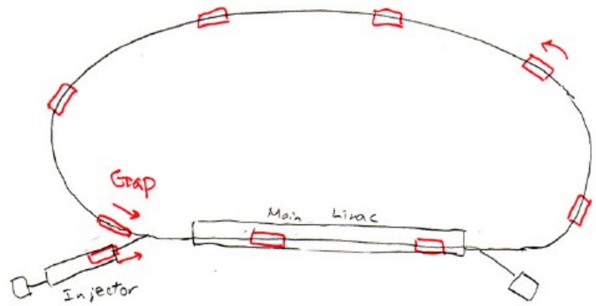
Deciphering Tom's paper

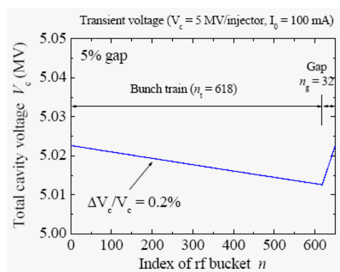
Questions from a complete beginner

- Why / how does energy recovery happen?
- What are r/Q, Q_L, Q_0, β, δf_S, ψ_B, …?
- How does the klystron power equation come about?
- What are microphonics, Lorentz detuning, ponderomotive effects, vector sum, … ?
- Why are we interested in detuning? What are mechanical tuners?
- Why is detuning measured by the Klystron-cavity phase difference?
- When Q_L is optimized, what exactly is minimised or maximised? The klystron power?
- Why is incomplete energy recovery needed? How does this compress the energy spread?
- What are page 2, page 3, page 4 and page 5 about?

Why Energy Recovery







(Sakanaka ERL07)

" … the beam-induced voltage in a cavity is the same whether or not a generator voltage component is present."
(Wilson 1991,
sect. 6.1 The Fundamental Theorem of Beam Loading)

The beam induced voltage is always negative.

Therefore, if a bunch enters at the opposite phase of the cavity field, it will increase the amplitude of the field.

This gives energy to the cavity.

Shunt Impedance

A full calculation from Maxwell's equations for pillbox cavit

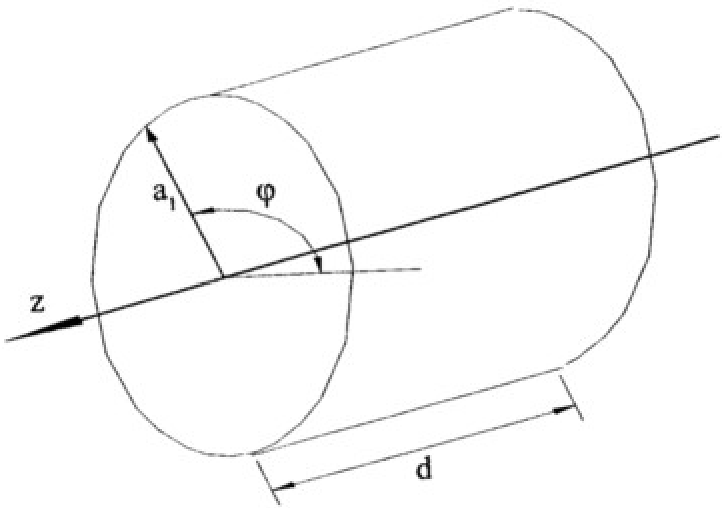


Fig. 6.2. Cylindrical resonant cavity (pill box cavity)

The total *cavity wall losses* become finally with $V_{\mathrm{cy}} = E_{\mathrm{o1o}}\, d$

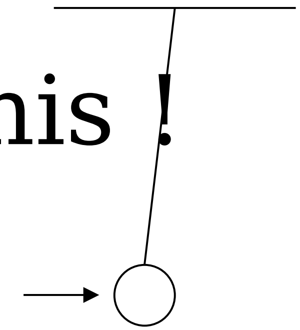
$$\boxed{P_{\mathrm{cy}} = [4\pi\epsilon_{\mathrm{o}}]\,\frac{\omega\delta_{\mathrm{s}}\epsilon}{8}\,\frac{\mu_{\mathrm{w}}}{\mu}\,V_{\mathrm{cy}}^2\,J_1^2(2.405)\,\frac{a_1(a_1+d)}{d^2}\,,} \qquad 56)$$

$$P_{\mathrm{cy}} = \frac{V_{\mathrm{cy}}^2}{2R_s}\,, \qquad (6.57)$$

$$\boxed{R_{\mathrm{s}} = [4\pi\epsilon_{\mathrm{o}}]^{-1}\,\frac{4}{\omega\delta_{\mathrm{s}}\epsilon}\,\frac{\mu}{\mu_{\mathrm{w}}}\,\frac{d^2}{a_1(a_1+d)}\,\frac{1}{\mathrm{J}_1^2(2.405)}\left(\frac{\sin\frac{\omega d}{2v}}{\frac{\omega d}{2v}}\right)^2 .} \qquad (6.58)$$

(Wiedemann 2003)

Many equations come from this !



Externally driven accelerating cavity: Accelerator cavities can be de scribed as *damped oscillators* with *external excitation*.

$$\ddot{x} + 2\alpha\dot{x} + \omega_o^2 x = D\,e^{i\omega t}\,, \tag{6.67}$$

complex amplitude A

$$A = \frac{D}{\omega_o^2 - \omega^2 + i2\alpha\omega} = a\,e^{i\Psi}\,. \tag{6.68}$$

cavity damping time

Q-value

$$t_d = \frac{1}{\alpha} = \frac{2\,Q}{\omega_r} \tag{6.73}$$

the solution

$$x(t) = a\,e^{i(\omega t + \Psi)} \tag{6.74}$$

out of synchronism by the phase Ψ

$$\cot\Psi = \frac{\omega^2 - \omega_r^2}{2\alpha\omega} \approx 2Q\,\frac{\omega - \omega_r}{\omega_r}\,, \tag{6.75}$$

(Wiedemann 2003)

Finding Answers

r/Q, Q_L, Q_0, β, ψ_B, …

This models
he behaviour of
he cavity voltages.

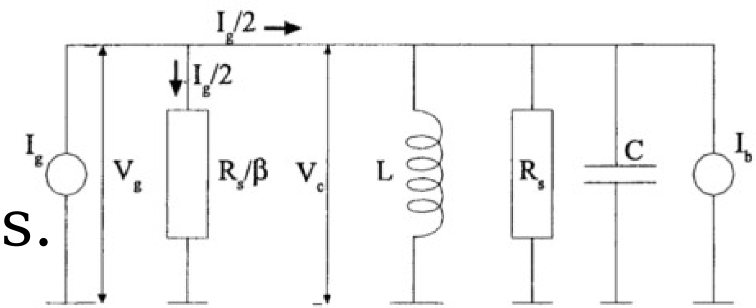


Fig. 6.6. Network model for an rf generator and an accelerating cavity

internal impedance of *generator*

$$R_g = \frac{R_s}{\beta}, \tag{6.76}$$

β is the *coupling coefficient*

rf power

$$P_g = \frac{1}{8}\frac{R_s}{\beta} I_g^2. \tag{6.81}$$

unloaded quality factor

$$Q_o = \omega_r C R_s, \tag{6.82}$$

quality factor for the total circuit as seen by the beam

$$Q = \omega_r C R_b = \frac{Q_o}{1+\beta}. \tag{6.84}$$

tuning angle

$$\tan\Psi \approx -Q\frac{\omega^2-\omega_r^2}{\omega_r\,\omega} \approx -2Q\frac{\omega-\omega_r}{\omega_r} \tag{6.88}$$

Mostly using equations from simple harmonic oscillator.

(Wiedemann 2003)

How the beam affects the cavity voltag

l voltages defined along the axis of cavity (beam path):

enerator (klystron) voltage V_g
eam induced voltage V_b
nd resultant cavity voltage V_c

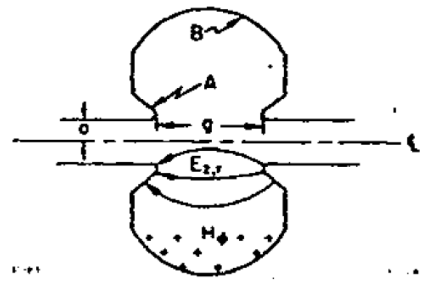


Fig. 3.2. Single Cell of a π-mode accelerating structure.

suming all sinusoidal, they can be related by a phasor diag

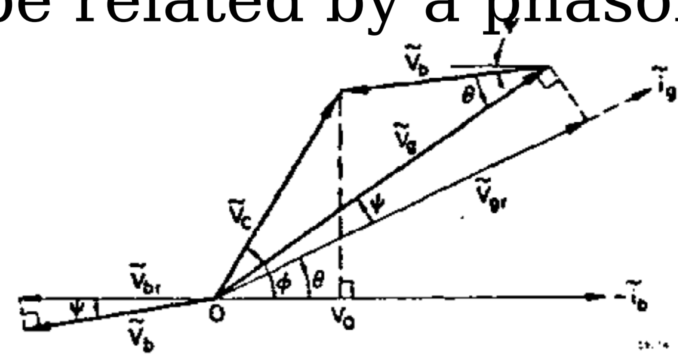


Fig. 3.13. Diagram showing the vector addition of generator and beam-loading voltages in an RF cavity.

(Wilson 1991)

The klystron power equation

r/Q, Q_L, Q_0, β, … are measured
by fitting to the equivalent circuit model

The klystron power can be calculated
from these parameters using the model.

Merminga (2001) explains how to get this:

$$P_g = \frac{V_c^2}{R_L}\frac{(1+\beta)}{4\beta}\left\{\left[1+\frac{I_0 R_L}{V_c}\cos\psi_b\right]^2+\left[\tan\Psi - \frac{I_0 R_L}{V_c}\sin\psi_b\right]^2\right\}$$

The main equation
in Tom’s paper

Steps are easy once we have worked from
Wiedemann and Wilson.

Energy recovery calculations

Nice examples from Merminga (2001)

- ERL Injector and Linac:

  δf_m=25 Hz, Q_0=1x10^{10} , f_0=1300 MHz, I_0=100 mA, V_c=20 MV/m, L=1.04 m, R_a/Q_0=1036 ohms per cavity

- ERL linac: Resultant beam current, I_{tot} = 0 mA (energy recovery)

  and β_{opt}=385 $\Rightarrow$ Q_L=2.6x10^7 $\Rightarrow$ P_g = 4 kW per cavity.

- ERL Injector: I_0=100 mA and β_{opt}= 5x10^4 ! $\Rightarrow$ Q_L= 2x10^5 $\Rightarrow$ P_g = 2.08 MW per cavity!

  Note: I_0V_a = 2.08 MW $\Rightarrow$ optimization is entirely dominated by beam loading.

Microphonics, Lorentz Force, Vector Sum

2.1 General Sources for Cavity Field Errors

Energy fluctuations of an accelerated beam along a linac are caused by various phenomena.

2.1.1 Microphonics

Mechanical vibrations caused by the accelerator environment are always present and may be transferred to the accelerating structures.

2.1.2 Lorentz Force Detuning

The objective is to reach high electromagnetic fields in superconducting structures. However, high electromagnetic fields in a cavity cause strong Lorentz forces acting on the walls. This deforms the cavity, leading to a change in the resonance frequency.

2.1.3 Calibration Error of the Vector Sum

RF sources like klystrons are expensive devices. The experience with existing klystrons has shown that many smaller units are more expensive than fewer high-power klystrons. A reduction of capital investment is to be expected if a large number of cavities are driven by one single klystron. In TTF / TESLA, it is planned to supply 32 cavities by a single 10 MW high-power klystron. For this reason, the RF control system has to control the vector sum of the accelerating fields of a control section of 32 cavities. Calibration errors in amplitude and phase of these individual fields result in an additional energy spread in the presence of microphonic noise. The measured vector sum and the actual vector sum seen by the beam differ on account of these errors. Even if a control system stabilizes the measured vector sum perfectly, the microphonic noise results in a different actual vector sum from macro-pulse to macro-pulse. This leads to different energy gains per control section. A control section is a string of cavities whose vector sum is controlled by one feedback system acting on the klystron which feeds the cavities. In Figure 2.2, the schematic of the measured and actual vector sum of eight cavities is displayed.

Revelation !

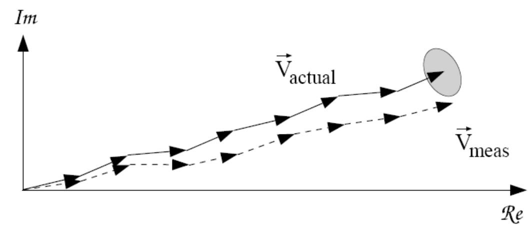
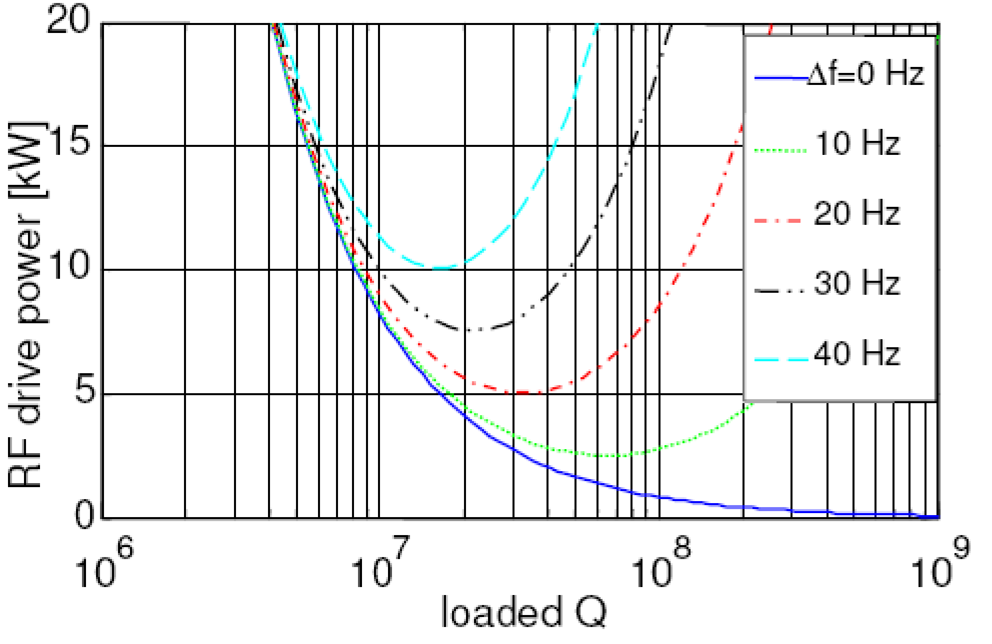


Figure 2.2: The measured vector sum of eight cavities with amplitude and phase calibration errors differs from the actual vector sum of the accelerating fields as seen by the beam. In the presence of microphonics, the actual vector sum fluctuates from macro-pulse to macro-pulse even with perfect amplitude and phase control.

(Schilcher 1998)

What exactly is being optimized?



(Liepe PAC05)

The klystron power, of course !

Ponderomotive force

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Ponderomotive force

From Wikipedia, the free encyclopedia

In physics, a **ponderomotive force** is a nonlinear force that a charged particle experiences in a rapidly oscillating, inhomogeneous electric or electromagnetic field. The ponderomotive force F_p is expressed by

$$\mathbf{F}_p = -\frac{e^2}{4\,m\,\omega^2}\nabla\mathbf{E}^2$$

where e is the electrical charge of the particle, m is the mass, ω is the frequency of oscillation of the field, and $\mathbf{E}$ is the amplitude of the electric or electromagnetic field. This equation means that an electron in an inhomogeneous oscillating field not only oscillates at the frequency of ω but also drifts toward the weak field area.

The mechanism of the ponderomotive force can be understood easily by considering the motion of the charge in an oscillating electric field. In the case of a homogeneous field, the charge returns to its initial position after one cycle of oscillation. In contrast, in the case of an inhomogeneous field, the position that the charge reaches after one cycle of oscillation shifts toward the lower field-amplitude area since the force imposed onto the charge at the turning point with a higher field amplitude is larger than that imposed at the turning point with a lower field amplitude, thus producing a net force that drives the charge toward the weak field area.

See also

[edit]

- Lorentz force

Finding Answers

Page 2 of Tom's paper

EFFECTS OF INCOMPLETE ENERGY RECOVERY

There are instances when it is necessary to operate an electron beam in a mode such that there is incomplete energy recovery, by which we mean the first and second pass beams are not 180° apart in phase. For instance in the Jefferson Lab IR Free Electron Laser (FEL) Upgrade we accelerate the first pass beam at 10° before crest in order to achieve bunch length compression and energy recover at 165° after crest to energy compress the large energy spread imposed on the beam by the FEL. This can lead to some interesting control issues.

Upon initial turn-on of the beam the klystron power and phase are given by the following.

$$P_{Kly} = \frac{(\beta+1)\,L}{4\beta\, R_C}\left\{ \left(E + I_0 R_C \cos\psi_B\right)^2 + \left(2Q_L \frac{\delta f_D}{f_0} E + I_0 R_C \sin\psi_B\right)^2 \right\} \quad (5)$$

$$\psi_{Kly} = \arctan\left(\frac{2Q_L \frac{\delta f_D}{f_0} E + I_0 R_C \sin\psi_B}{E + I_0 R_C \cos\psi_B}\right) \quad (6)$$

The cavity RF system resonance control algorithms typically adjust the tuner until the phase difference between the klystron power and the field probe signal is set to its baseline value. Thus the mechanical tuner will shift the cavity frequency, δf, such that the average value of the numerator in Equation (6) is zero and the forward power is reduced. If one gives this added frequency shift the label δf_{S1} then the equation for the klystron power becomes:

$$P_{Kly} = \frac{(\beta+1)\,L}{4\beta\, R_C}\left\{ \left(E + I_0 R_C \cos\psi_B\right)^2 + \left(2Q_L \frac{(\delta f_D + \delta f_{S1})}{f_0} E + I_0 R_C \sin\psi_B\right)^2 \right\} \quad (7)$$

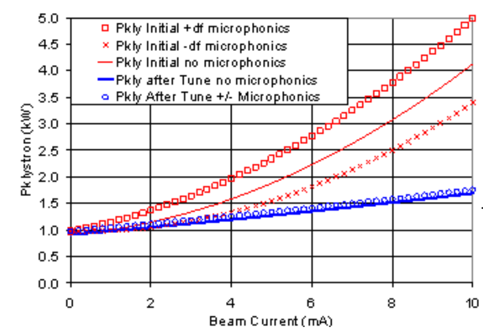
where

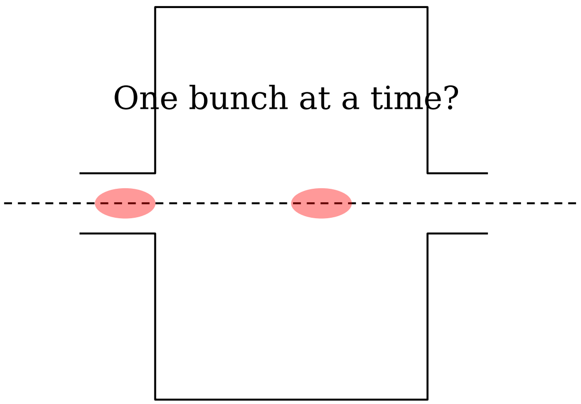
$$2Q_L \frac{\delta f_{S1}}{f_0} E = -I_0 R_C \sin\psi_B \quad \text{or} \quad (8)$$

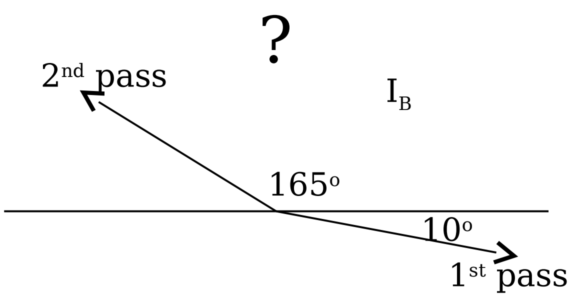
Consider the next situation. The cavity tuners have completed the process of compensating for the reactive power and the forward power is now back at the baseline phase difference with the transmitted power signal. Suddenly, the beam turns off. It can be easily shown that when the beam current is turned off, the cavity starts out detuned by δf_{S1} and experiences an equal power transient and an equal, but negative, phase transient compared to the beam turn on transient. Again just as in the turn on transient the RF system must compensate for this transient until the cavity tuner has time to adjust the cavity length and reestablish the baseline phase difference between the forward and transmitted power.

An Example of Incomplete Energy Recovery

Consider the following scenario; first pass beam at a phase of 10° before crest, second pass beam at 165° after crest and a beam current of I_B. In theory this is the situation when the FEL is lasing with 2.5% extraction efficiency [4]. Simple vector math can be used to determine that the resultant beam current is $I_0 = 0.087 \times I_B \angle 77.5°$. Figure 1 shows the power requirements for a 7-Cell JLAB upgrade cavity as a function of average beam current. The cavity parameters are $E = 10$ MV/m, $\delta f_D = 10$ Hz, and $Q_L = 2\times10^7$.







Shall try to do this ne

Experiments

- References on Feedback control
  - Stefan Simrock’s LLRF lectures
  - Papers on ELBE rf system

- Andy’s Rossendorf control unit
  - Connect control system to standalone cavity
  - Stretched wire measurements with short pulses

- Ideas for experiments
  - For learning about rf control
  - For modelling of beam loading / energy recovery